FIELD OF THE INVENTION

The present invention relates to a method of measuring local similarities between several prestack 3D seismic trace cubes obtained from a volume of an underground zone, or after repetitive prospecting surveys (4D) for example. It therefore is a local coherence measurement giving in the first place the similarity of a seismic cube in relation to another one, while taking account of the local similarity within a single cube.

BACKGROUND OF THE INVENTION

The notion of coherence proper is a relatively recent notion. Until now, the issue was to develop a tool revealing the stratigraphic or structural changes (notably faults) from seismic measurements, and thus to obtain volume information on these changes. The foundation of all the methods developed for less than ten years consists in defining a local dissimilarity from trace to trace.

A first algorithm described by : **Bahorich, M., and Farmer, S.** (1995), "The coherence cube", *The Leading Edge*, **14**, 10, 1053-1058, consists in calculating the crosscorrelation between each trace of a seismic cube with its two in-line neighbours, with its two CDP (common depth point) neighbours, then in combining the two results, after normalizing them by the energy of the traces. The coherence is estimated only from three traces, which makes calculation very fast but not very robust if the data contains noises.

According to another algorithm described by **Marfurt, K.J., et al.** (1998), "3-D Seismic Attributes Using a Semblance-based Coherency Algorithm", *Geophysics*, **63**, 1150-1165, the coherence calculation is based on a local semblance calculation involving more traces, which makes the result more robust to noise.

According to another algorithm described by **Gersztenkorn, A., and Marfurt, K.J.** (1999), "Eigenstructure based Coherence Computations as an Aid to 3-D Structural and Stratigraphic Mapping", *Geophysics*, **64**, 1468-1479, the coherence calculation is based on an expansion into eigenvalues : an analysis window defined in lines, CDP and time is extracted from the seismic cube, the seismic trace covariance matrix is formed and the largest eigenvalue of this matrix is calculated. The coherence value then corresponds to the ratio between this eigenvalue and the sum of all the eigenvalues of the covariance matrix, or trace of the covariance matrix, which is the total variance of the seismic traces of the analysis window.

All these approaches however have certain limits. In particular, a major limitation is that they are not applicable to the analysis of seismic multicube data.

In fact, the goal of these various coherence attributes is rather to map stratigraphic anomalies; they therefore do not allow to evaluate the coherence, either calendar (4D) or AVO ("Amplitude Versus Offset"). As far as we know, there is to date no algorithm allowing to determine such attributes.

Generalized Principal-Component Analysis (GPCA) is a known tool allowing to show a possible information redundancy between groups of seismic attributes; it can be suited for defining a local seismic data similarity measurement, from one cube to another, by analysing a neighbourhood around a current point, the notion of group of attributes being related to the various surveys in time or to the various prestack seismic surveys for example.

This technique is implemented in the method described in patent application FR-02/11,200 filed by the applicant, for compacting and filtering seismic events read on "multicube" seismic traces, with distribution of these events in families corresponding

each to a particular physical meaning : iso-offset or iso-incidence angle data cube, elastic parameter cubes resulting from a joint stratigraphic inversion, etc., in order to extract information on the nature of the subsoil. This method essentially comprises forming, by combination of the seismic variables, synthetic variables in much smaller number, obtained by construction of an orthogonal vectorial base in each one of the analysis sets consisting of the data of each family, hence formation of an orthonormal vectorial base describing these analysis sets, and use of this orthonormal vectorial base (new attributes) for filtering and describing said seismic events.

SUMMARY OF THE INVENTION

The method according to the invention provides measurement of the local similarity between several 3D prestack or 4D (repeated in time) seismic data cubes. The method comprises the following stages :

a) at each point of the volume studied and characterized by several seismic cubes, extracting a volume neighbourhood centred on this point (current point) and consisting of a set of seismic traces in limited number; thus, each current point is characterized by as many groups of seismic attributes as there are cubes analysed;

b) applying the GPCA analysis technique to these groups of seismic attributes extracted from each seismic cube in the volume neighbourhood of the current point to form synthetic variables;

c) determining a coherence value from the synthetic variables extracted, which is assigned to the current point;

d) repeating stages a) to c) for each point; and

e) grouping all of the coherence values into a coherence cube.

The values contained in this coherence cube give the degree of local similarity sought between the seismic data cubes.

The projections of the synthetic variables on the various cubes in the neighbourhood of the current point represent part of the information of the corresponding group. This information or variance part is known. Consequently, several approaches can be considered for calculation of the coherence attribute from the correlation values calculated between the synthetic variables and their projections on the cubes in the neighbourhood of the current point.

According to an implementation mode, for each point, the coherence value taken is the mean value of the squares of the correlations between the synthetic variables and their projections on the cubes in the neighbourhood of the current point, on a limited number k of said synthetic variables.

The value of k is determined, for example, as the smallest number of synthetic variables allowing to reach a variance threshold explained by the projections of the synthetic variables on each cube, this threshold having been previously determined.

According to another implementation mode, a number of synthetic variables is selected depending on their correlations with the groups of attributes associated with the volume neighbourhood of the current point. The coherence value assigned to the current point is equal to the weighted sum of the squares of the correlations between the synthetic variables considered and their projections on the cubes in the neighbourhood of the current point.

For a correlation value, the weighting value selected is for example the variance percentage explained by the projection of the synthetic variable on the corresponding

group divided by the sum of the variances of all the projections of the synthetic variables considered on the same group.

According to another implementation mode, a threshold is set on the variance percentage explained by the projections of the synthetic variables on the cubes, in the neighbourhood of the current point, that has to be taken into account. The coherence value is then equal to the weighted sum of the squares of the correlations between the synthetic variables and their projections on the cubes in the neighbourhood of the current point, so that the number of synthetic variables taken into account allows this threshold to be reached.

For a determined correlation value, a weighting value equal to p (number of cubes) times the set variance threshold is for example selected.

As the case may be, the volume neighbourhood can be extracted from seismic trace cubes obtained either after a 3D seismic survey, each one corresponding to the same incidence angle or to the same offset, or after successive seismic exploration surveys in the zone.

The volume neighbourhood can also be extracted from residue cubes obtained either after a prestack stratigraphic inversion or from residue cubes obtained after a poststack stratigraphic inversion. It can also be extracted from the inverted cubes (prestack or poststack) and from the residue cubes.

The method is particularly advantageous in that it allows to define a new attribute measuring a local similarity between several seismic cubes extracted from a neighbourhood around a point. It allows to take account of the multicube aspect of the seismic data and measures more the variability from one seismic cube to another than the variability within a single cube.

BRIEF DESCRIPTION OF THE FIGURES

- Figure 1 shows the extraction of seismic cubes for coherence analysis, in the neighbourhood of a current point,

- Figure 2 shows the projections of synthetic variable $Z^{(j)}$ on groups 1 and k,

- Figure 3 shows the seismic cubes (a), (b) and (c) obtained after three repeated seismic surveys and the associated coherence cube (first implementation mode or approach) – Time window outside the reservoir,

- Figure 4 shows lines extracted from the coherence cube – (a) line 10, (b) line 20, (c) line 30, (d) line 40,

- Figure 5 shows a plane located 28ms below the top extracted from the cubes of the same three surveys and the same coherence cube,

- Figure 6 shows line 10 extracted from the coherence cube calculated according to the first implementation mode with a 99 % threshold (a), according to the third mode with a 99 % (b), 90 % threshold (c), according to the second implementation mode with the first synthetic variable (d), the first two synthetic variables (e),

- Figure 7 shows examples of distribution of the amplitude differences between two seismic surveys,

- Figure 8 shows the seismic cubes associated with the three successive surveys and the associated coherence cube, in a time window at the level of the reservoir,

- Figure 9 shows the temporal planes extracted from the coherence cube calculated on the reservoir,

- Figure 10 shows the temporal plane located 12ms below the top of a reservoir and the coherence attribute calculated with the first synthetic variable (a), the first two synthetic variables (b), with a 90 % (c), 95 % (d), 99 % (e) variance threshold,

- Figure 11 shows a 3D view of the coherence cube obtained with the first two synthetic variables (second approach) – coherence values strictly below 0.8,

- Figure 12 shows iso-angle 0°-6°, 12°-18°, 24°-30° seismic cubes and the associated coherence cube,

- Figure 13 shows three temporal planes located (a) 4ms, (b) 10ms, (c)16ms below the top of the reservoir and extracted from the coherence cube, and

- Figure 14 shows a line passing through a well W2 extracted from the 0°-6°, 12°-18°, 24°-30° seismic cubes and from the coherence cube.

DETAILED DESCRIPTION

The notion of coherence has especially been applied so far for seeking stratigraphic anomalies and the coherence values calculated from a single seismic data cube, usually the poststack cube.

With the method described hereafter, a coherence cube is formed from several 3D seismic data cubes (AVO or 4D) showing at any point the degree of local similarity or dissimilarity of the seismic data, cube to cube, on a volume neighbourhood around a current point, and thus allowing to map what changes or does not change from one cube to the next.

As reminded above, GPCA is a technique allowing to show what is common and what is different between p groups of variables or of seismic attributes, and to rapidly determine if all the groups are linearly identical. Calculation of a coherence cube

consists in carrying out a local measurement of the similarity (or dissimilarity) from one seismic cube to another, while taking also into account the local similarity around the current point within a single cube.

Let us consider p seismic trace cubes. These trace cubes can correspond, for example, to poststack seismic surveys repeated in time in a single geographic zone (4D seismic cubes), or to iso-angle or iso-offset prestack 3D seismic cubes.

A volume neighbourhood centred on a coordinate (Line; CDP (common depth point), time and depth) and consisting of a limited number of traces is extracted from each one of the p seismic cubes (Figure 1). The number of traces forming this neighbourhood will be dealt with below. We thus have p sets of traces of equal dimension centred on a point of equal geographic coordinates, and corresponding to the p initial seismic cubes.

A GPCA is carried out on the p sets thus extracted. Each set thus extracted in the neighbourhood of the current point corresponds to a group of initial seismic attributes, these attributes being simply, for example, the series of the amplitude values corresponding to the different values of the trace in the time window studied. The total number of attributes is thus equal to p times the vertical dimension of the neighbourhood considered.

We then calculate the square of the correlation between synthetic variable $Z^{(j)}$ and its projection on a group of attributes (Figure 2). The square of the correlation corresponds, in fact, to the square cosine of the angle θ between the two vectors representing respectively the synthetic variable and its projection. It gives an indication of the degree of proximity between these two vectors, and therefore between synthetic variable $Z^{(j)}$ and the corresponding group; a value 1 indicates that the synthetic variable

and its projection merge, whereas a value far from 1 gives an indication of the distance between them.

Thus, when all the groups of attributes are similar to each other, the square cosines of the angles between all the $Z^{(j)}$ and their projections are equal to 1. In the opposite case, when the similarity is weak, the squares of the correlations are more or less far from 1 for a certain number of $Z^{(j)}$; they are all the further therefrom, for a certain number of them, as the groups of attributes are different.

Now, the projections of each $Z^{(j)}$ on the various groups represent part of the information of the corresponding group. This variance part can be known and calculated. Several approaches can then be considered for calculation of the coherence attribute from these correlation values.

First approach

A simple first approach consists in calculating the mean value of the squares of the correlations on a number k of $Z^{(j)}$ ($k \leq p$). Number k is selected as follows :

(i) a threshold S on the cumulative variance is set, for example 90 %,

(ii) k is then determined as the smallest number of synthetic variables $Z^{(j)}$ allowing this threshold to be reached.

In this case, the number of synthetic variables considered in the calculation of the correlations is identical for each group and the weight assigned to each correlation is the same.

$$c = \frac{1}{p \times k} \sum_{i=1}^{p} \sum_{j=1}^{k} \rho^2 (Z^{(j)}, Z_i^{(j)})$$

Second approach

A second approach consists in selecting the number of synthetic variables $Z^{(j)}$ according to their correlation with the groups : in general, the first variables are sufficient because, by principle, they represent the part of the information common to the groups.

Once this number set, and unlike the first approach, the sum, weighted by the variances, of the squares of the correlations between the $Z^{(j)}$ considered and their projections on the groups is calculated. The squares of the correlations between a vector $Z^{(j)}$ and its projections on the various groups can in fact all be equal to 1, whereas the explained variance part is small.

Weighting by the variance then allows to take account of the compaction capacity of the synthetic variables extracted from the GPCA in the coherence calculation, and to avoid assigning too great a value if, in reality, the trace cubes studied are similar only in a small way. In this case, the weight $p_{i,j}$ assigned to each correlation is equal to the variance explained by the projection of synthetic variable $Z^{(j)}$ on the corresponding group i, divided by the sum of all the variances. This "normalization" ensures that the sum of the weights is equal to 1.

$$c = \sum_{i=1}^{p} \sum_{j=1}^{k} p_{i,j} \times \rho^2 (Z^{(j)}, Z_i^{(j)})$$

Besides the weighting difference with the first approach, it can be noted that the variance part taken into account in each group can be different.

Third approach

Finally, a third approach consists, as in the first approach, in setting a threshold on the total explained variance part to be taken into account. But this time, for each group i, the number k_i of synthetic variables $Z^{(j)}$ considered will be strictly the number allowing the threshold to be reached. Thus, this number can be different from one group to the next. The "mean" correlation will be estimated with all of the elementary correlations of the synthetic variables required for each group.

$$c = \sum_{i=1}^{p} \sum_{j=1}^{k_i} p_{i,j} \times \rho^2 (Z^{(j)}, Z_i^{(j)})$$

The weight $p_{i,j}$ given to each correlation is then equal to the variance explained by the projection of the synthetic variable $Z^{(j)}$ on group i divided by p times the variance threshold selected. This "normalization" thus allows to have a sum of weights equal to 1.

Two parameters characterizing the size of the analysis neighbourhood around the current point have to be determined : the number of traces of the neighbourhood and the vertical dimension (in time or depth) of the traces. If a small number of traces is taken into account, for example nine traces per neighbourhood, the result will spatially appear to contain more noise than if each neighbourhood consists of more traces, 25 for example. On the other hand, the greater the vertical dimension, the more the coherence result can be expected to be vertically smoothed. Furthermore, as the variability can increase, the variance threshold to be set in the coherence attribute calculation according to the third method will be different depending on the vertical dimension of the analysis window. Similarly, the compaction capacity of the synthetic variables can be expected to be all the higher as the dimension of the window is small.

APPLICATION EXAMPLES

1 - Application to 4D seismic data

Repeated seismic methods consist in carrying out several seismic surveys in a single geographic zone in order to analyse and to map the changes that may occur in a reservoir after production has started. Calculation of a coherence attribute on 4D data has two goals :

1) indicate more precisely the reproducibility of the seismic signal outside the reservoir and thus to control the homogenization process of the seismic amplitudes,

2) indicate where and to what extent the seismic response varies within the reservoir and therefore help to interpret these changes.

We used the seismic traces of three poststack cubes corresponding to three 3D seismic surveys, from which three 60-ms thick cubes located approximately 70 ms above the reservoir and three 20-ms thick cubes located at the reservoir level were extracted.

The aim of analysis of the cubes outside the reservoir is to study to what extent the seismic signal is repeated from one survey to the next, whereas analysis of the seismic cubes located at the reservoir level allows to study the variations of the seismic method with time, induced by the reservoir development.

1-1 Outside the reservoir

A coherence attribute was first calculated according to the first calculation method on a part located well above the reservoir (70ms) so that the seismic records are not influenced by the reservoir development. The variance threshold was set to 99 %, thus allowing to take account of almost all of the information explained by the synthetic

variables extracted from the GPCA, and also not to take into account synthetic variables explaining too small a part of the variance. The size of the neighbourhood of the current point used for calculation of the coherence is 25 traces (a 5-trace side cube centred on the current point) of 4ms each. Figure 3 shows the three seismic cubes corresponding to the three surveys, and the associated coherence cube. Contrary to what could be expected, it shows that the three surveys are not perfectly coherent since values below 0.7 are obtained.

The three seismic surveys seem to be relatively coherent on the first 22 ms with a majority of values above 0.8 (Figure 4). Beyond that figure, there are locally more zones having a low coherence value, with a majority of values ranging between 0.7 and 0.8 and, locally, values below 0.7.

This is illustrated by Figure 5 which shows the temporal plane, located +30ms below the top of the cube, for the three seismic surveys and the coherence cube. The values below 0.8 are the majority and are distributed throughout the temporal plane. The record sections of the three surveys confirm this lack of 4D coherence.

The coherence cubes according to the other two methods were also calculated from the same seismic cubes.

Figure 6 shows line 10 extracted from the coherence cubes calculated according to the first method with a threshold set at 99 % (a), according to the third method with a threshold of 99 % (b), 90 % (c), according to the second method with the first synthetic variable (d), the first two synthetic variables (e).

All the sections obtained are globally quite similar. Section (c) shows higher coherence values than section (b) : the additional variance part taken into account

therefore seems to correspond to a less common local information part, thus causing the coherence to move downwards.

The coherence values seem to be a little higher when they are weighted by the variance than when a simple average is calculated. Section (e) is similar to section (b) and section (d) is similar to section (c) : it therefore seems that, in most cases, locally, two synthetic variables are enough to summarize all of the information.

Section (e) has a little more low-coherence values than section (d). Similarly, the zones of very high coherence (values above 0.9) are a little less large in the second case. On the other hand, the coherence slightly increases in some few zones. Globally, the results obtained are not fundamentally different, although addition of the second synthetic variable to the coherence attribute calculation causes more variance to be taken into account. Addition of the second synthetic variable thus confirms the similarities or dissimilarities that had already been observed with a single attribute synthetic variable. In conclusion, for this analysis carried out outside the reservoir, a single synthetic variable can be enough to calculate the coherence attribute.

The results are not detailed here, but it has been checked that, when decreasing the number of traces defining the neighbourhood (9 instead of 25), the coherence cubes obtained have a spatially more noise-containing aspect. Similarly, it has been checked that, by increasing the vertical dimension of the seismic traces, the coherence cube obtained is vertically smoothed : in this case, the very low coherence values observed in Figure 5 are slightly higher. When taking account of two or three synthetic variables, or when setting a 99 % variance threshold, there are fewer zones with low coherence values.

Whatever the method, it appears that the cubes located outside the reservoir are not totally coherent : this may be due to an imperfect amplitude homogenization process, or to a certain influence of the reservoir development on the amplitudes.

Figure 7 shows the distributions of the amplitude differences between two successive surveys several years apart, within the time window studied. In case of perfect signal reproducibility, the median or mean values should be centred on 0, and the distributions should not be very spread out. Now, it clearly appears that this hypothesis is correct only between 8 and 24 ms in the example considered. Elsewhere, the distributions fluctuate around 0, with a maximum median value reached at about 30 ms. This global amplitude difference measurement therefore confirms the more local result obtained with the coherence attribute.

1-2 In the reservoir

A coherence attribute was then calculated within the reservoir according to the first method. The variance threshold was set to 99 %. The dimension of the neighbourhood of the current point for calculation of the coherence is 25 traces of 4 ms each. The reservoir zone corresponds to a 20-ms thickness.

Figure 8 shows the three seismic surveys and the associated coherence cube. The zones showing the lowest coherence values seem to be located at the base of the reservoir, in the southern two thirds. The coincidence between the location of the wells allowing production and the low coherence values backs up the interpretation in terms of 4D variations and not simply in terms of seismic noise, as might be done considering the non-perfect reproducibility of the signal shown above with the coherence attribute in the zone outside the reservoir.

This is confirmed by Figure 9 showing the eleven temporal planes of the coherence cube. Although it is not totally immutable, the northern third seems not to change from one survey to the next, with coherence values mainly above 0.8 over the total thickness of the reservoir; slight variations can however be observed between CDP 80 to 90 and lines 14 to 20 for the planes located 12ms to 16ms below the top of the reservoir. The south-eastern corner of the reservoir also remains unchanged from one survey to the next. These zones therefore seem not to be too much influenced by the field development : they can be considered as a reservoir zone of lower quality in terms of porosity/permeability.

The wide zones of very low coherence values at the base coincide with the presence of three of the four steam injection and oil recovery wells, as well as in the southern part below these wells, which points to an invasion by the steam injected in this zone. Similarly, the zone of very low coherence at the top is located plumb with the end of the four wells : here again, this zone can correspond to steam rising at the end of the wells.

On the other hand, the northernmost well coincides with a slightly more coherent zone beyond line 80. This well is located at the boundary with the zone considered to be a less good reservoir; the steam injected could influence more the part located more south to this well.

Figure 10 shows the temporal plane located 12ms below the top of the reservoir extracted from the coherence cubes calculated according to the other two approaches : for the first method by taking into account a single synthetic variable (a), two synthetic variables (b), for the second method by setting a 90 % (c), 95 % (d) and 99 % (e) variance threshold. The two maps (a) and (b) are very similar, but they are also very similar to maps (d) and (e) respectively. Addition of a second synthetic variable, as for

the outside-the-reservoir case, does not seem to change the interpretation that could be given. Globally, it seems that two synthetic variables are enough to explain almost all of the initial variance of each group of attributes analysed. Similarly, taking into account the additional variance between maps (d) and (e) does not change the coherences obtained, except for small details. On the other hand, map (c) appears to be much more coherent than the other two maps. The additional local variance part taken into account thus corresponds, in most cases, to information that is less common to the three cubes considered. The coherence values obtained in this case are higher than the coherence values obtained by means of a simple average (see the corresponding map in Figure 9).

Figure 11 shows a 3D view of the coherence cube obtained with two synthetic variables and grouping together the coherence values strictly below 0.8. It clearly appears that the northern third is unchanged, as well as the north-eastern corner. Similarly, only the two thirds at the south seem to change.

2 - Application to prestack seismic data

The methodology can also apply to prestack seismic surveys : in this case, the existence of coherent zones in the AVO data has to be determined from several iso-angle or iso-offset 3D seismic cubes.

The data used consist of the five iso-angle cubes covering an oil reservoir (channel with gritty deposits). The thickness of the sequence studied is 38ms.

The size of each neighbourhood is 5 lines by 5 CDP, i.e. a total of 25 traces. The vertical dimension taken is 4 ms, i.e. three time samples. The coherence cube was calculated according to the first method (simple average) with a 99 % variance threshold.

Figure 12 shows three of the five iso-angle cubes used (0°-6°, 12°-18° and 24°-30° cubes), as well as the coherence cube obtained. In the latter cube, the most coherent zones appear in orange and red, and the least coherent zones in green and blue. The borders of a channelling structure clearly appear in form of coherent zones.

Globally, the least coherent zones are essentially located in the upper part of the reservoir window studied (Figure 13, map a), except for a very coherent small zone in the northwest corresponding to a great amplitude anomaly that can be seen in all the angle cubes.

In the median part (map b), the most coherent zones follow the outline of the channelling shape, the channel itself corresponding to coherence values below 0.8. In the lower part of the window (map c), there are fewer incoherent zones which are essentially located in the northeast and in the southwest.

The least coherent zones seem to highlight seismically more blind zones or seismic zones for which the markers are not observed from one angle cube to the next.

Figure 14 shows the line passing through a well W2, extracted from the 0°-6°, 12°-18° and 24°-30° seismic cubes, and the same line extracted from the coherence cube. The zones corresponding to the channels are relatively well marked by low coherence values in the upper part thereof, and by higher values in the lower part. The coherent zones correspond to high-amplitude markers that can be found in the various angle cubes.

It has also been checked that, by decreasing the number of traces taken into account in the neighbourhood, the coherence cube obtained takes a more noise-affected aspect. Similarly, it has been checked that, when increasing the vertical dimension of the

seismic traces of the neighbourhood, the coherence cube obtained is vertically smoothed.

The AVO coherence attribute thus shows the degree of coherence of the seismic cubes extracted in the neighbourhood of the points and considered as a function of the angle. Consequently, the incoherent zones can be interpreted either as seismic noise or as particular lithologic facies, transparent from a seismic point of view (i.e. showing no reflectors), or as great amplitude variations as a function of the angle (due to the fluid content for example). It is therefore interesting to take account of this coherence attribute in the interpretation of reservoirs, as a complement to other attributes.